

On QGP Formation in pp Collisions at 7 TeV

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The possibility of QGP formation in central pp collisions at ultra-high collision energy is discussed. Centrality-dependent p_t -spectra and (pseudo)rapidity spectra of thermal photons (charged hadrons) from pp collisions at 7 TeV are presented (addressed). Minimal-bias p_t -spectrum of direct photons and charged hadrons is compared under the framework with and without hydrodynamical evolution process.

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I. INTRODUCTION

It is believed that all matter in our universe was in a state called as the Quark Gluon Plasma (QGP) shortly after the creation of the universe in the Big Bang. At the mean while, high temperature/density matter is created in laboratories with high energy accelerators. In Relativistic Heavy Ion Collider (RHIC), there are many important classes of experimental observations, such as:

- Suppression of high p_t hadrons
- Back-to-back dihadron correlation
- The scaling of elliptic flow
- Direct photon enhancement at low p_t
- ...

They imply QGP formation in central heavy ion collisions at very high energy. The detailed microscopic evolution procedure of the collision system is not yet fully understood, because one kind of bricks in the process, the interactions of quarks and gluons with small momentum exchange, *i.e.*, below Λ_{QCD} , is barely known. Nevertheless, direct photons are regarded as an ideal probe of the evolution procedure of the collision system due to two reasons:

1. They can be produced during the whole evolution via the interaction (soft and hard) between quarks and gluons, and the interaction between hadrons.
2. They can penetrate the collision system without further interaction because of their big mean free path.

By definition, one can imagine the creation of a QGP in proton-proton collisions at ultra-high energies from the intuition. The problems are mainly two aspects:

1. How to construct a reliable calculation in order to learn more;
2. What are the sensitive signals for QGP formation in pp collisions.

In the following sections, we will focus on the two questions, especially on soft physics, *i.e.*, the production of the most copious particles.

II. HOW TO CONSTRUCT THE CALCULATION?

First of all, we have to classify the centrality. In heavy ion collisions, this is determined by how many pairs of nucleon collisions, measured via the multiplicity or the transverse energy (at midrapidity region). In pp collisions, centrality looks like a strange word. But centrality becomes important in pp collisions with the increase of the collision energy \sqrt{s} because partons at low- x in proton becomes more and more active. We will see the details in the following.

In AA collisions, pairs of nucleons from projectile and target interact in parallel at early stage, followed by many secondary interactions. Now we are treating the early stage of pp collisions, where pairs of partons from projectile proton and target proton interact in parallel. While the former one is treated with Glauber model, the latter one can be treated with Gribov theory [1]. Two examples of centrality in pp collisions are shown in Fig.1. Example (a): only two quark-diquark strings are excited between projectile proton and target proton to produce particles. Example (b): two gluons are emitted additionally, one from projectile proton and the other from target protons, and convert into a quark and an antiquark at each side, then two pairs of quark-antiquark interaction between projectile and target are formed. More pairs of

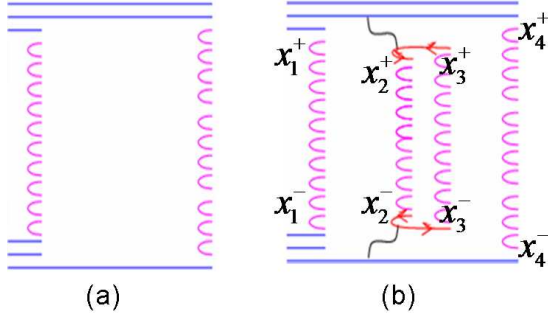


Figure 1: (Color Online) Two examples of centrality in pp collisions. For details see the text. Energy momentum fractions x_i^+ and x_i^- in (b) are labeled. Picture comes from [3].

partonic interaction can occur through more gluon emissions, which provide more central pp collisions.

How is the centrality study relevant to collision energy \sqrt{s} ? In Fig.1(b) energy momentum fractions x carried by partons from protons are labeled for more convenient discussion. A chain of quark and antiquark (or diquark) between projectile and target is called as a string. The string has a total energy $x^+x^-\sqrt{s}$, where x^+ and x^- are the energy momentum fractions of the partons at projectile and target side, respectively. Partons at two ends of strings will fly away according to their energy and momentum. A string will break when its two ends becomes further and further, because the $q\bar{q}$ linear potential should not exceed the total energy of the string. The fragments of strings are the hadrons produced. Partons at low- x in proton becomes more active with the increase of the collision energy \sqrt{s} , because the energy threshold for strings to produce particles remains the same:

$$x^+x^-\sqrt{s} > E_0,$$

where E_0 is an energy scale around 1 GeV. Thus, an ultra-high collision energy \sqrt{s} means partons at very low x are energetic enough to go out the Dirac sea and involve particle production. Because the density of partons in a proton increases rapidly with the decrease of x , many low- x partons may form strings to produce particles. So at ultra-high collision energy, the number of strings may fluctuate largely from event to event, and the classification of centrality becomes important.

Let's make a comparison of centrality between AA collisions and pp collisions to see more details:

1. In the case of AA, the phase space distribution of nucleons in a heavy nuclei is much simpler. The spatial distribution is the widely tested Wood-Saxon type. The total number of nucleons in a heavy nuclei is the mass number A and the total energy is almost equally shared by them. In the case of pp, each sampling of parton energy from a proton should obey the parton distribution function in proton (PDF). However, the PDF at low- x is

much less explored. There are also constraints from conservation law, *i.e.*, energy conservation requires $\sum_i x_i = 1$ at both projectile and target sides.

2. In the case of AA, the reference of pp collisions can be fully studied directly, concerning to all kind of observables. In the case of pp, the reference of partonic collisions can only be obtained indirectly, *i.e.*, via $e^+e^- \rightarrow q\bar{q}$ process, due to quark confinement. The main parameters of string fragmentation have been determined phenomenologically.
3. In the case of (central) AA collisions, many particles are produced from the collisions of nucleon pairs, then secondary interaction between produced particles cannot be ignored. A large number of secondary interaction in the collision system can be treated macroscopically with hydrodynamics. In the case of (central) pp collisions at very high energy, many particles are produced from the collisions of many parton pairs, too. The secondary interaction between produced particles cannot be ignored, either. We also take hydrodynamics to treat the evolution of the many-body system.

So we construct the calculation like this:

1. Initial condition [4]: For each given centrality of pp collisions, the initial energy momentum tensor is obtained from strings or string fragments via:

$$T_{\text{hydro}}^{\mu\nu}(\tau_0, \vec{r}) = T_{\text{particle}}^{\mu\nu}(\tau_0, \vec{r}) \equiv \frac{\sum_{i \in \Delta V} p_i^\mu p_i^\nu}{\Delta V}.$$

2. Evolution: The evolution of energy momentum tensor is governed by the conservation law,

$$\partial_\mu T^{\mu\nu} = 0,$$

solved in full 3+1D space-time (τ, x, y, z) with equation-of-state taken from Lattice results, then decomposed as the following terms:

$$T^{\mu\nu} = (e + P)u^\mu u^\nu - Pg^{\mu\nu} + \Pi^{\mu\nu},$$

to obtain energy density e , pressure P , local four flow velocity u^μ , where $g^{\mu\nu} = \text{diag}(1, -1, -1, -1)$ is the metric tensor and the viscosity term $\Pi^{\mu\nu}$ is set to zero in ideal hydrodynamics.

3. Freeze-out: We take the same freeze-out condition as in heavy ion collisions, *i.e.*, $e^{th} = 0.08 \text{ GeV/fm}^3$ or $T^{th} = 100 \text{ MeV}$. Thus soft hadron production can be obtained with the Cooper-Fry formula.

Thermal photons can be produced during the whole evolution procedure, calculated via photon emission rate with the above obtained local temperature and flow velocity. Thermal photons are the main source of direct photons at low transverse momentum region, as we know

from heavy ion collisions, similar to the soft hadron production from the bulk.

One may argue that the pp collision system is too small to employ hydrodynamics. This is first a question of collision energy and collision centrality. At low collision energies, the pp collision system has a small size. But at ultra-high collision energies, there is a big fluctuation of centrality, as we discussed above. Thus, for the central pp collisions at very high energy, a relatively big size may be formed, *i.e.*, implied by the Bose-Einstein correlation or HBT study.

At the other hand, a high energy density region must be formed when the two highly compressed protons are overlapped. Then many constituent particles in the system are partons due to the high energy density, whose mean free path may be very small, because $\lambda^{-1} = \rho\sigma$ and

1. the cross section of soft partonic interaction σ is not precisely known, but quite big due to strong coupling at the non-perturbative region;
2. The parton density ρ is certainly very high at high energy density.

Thus the employment of hydrodynamics might be legal. Anyway, our knowledge on the properties of the created quark matter is very limited.

III. CENTRALITY DEPENDENT RESULTS AND MINIMAL-BIAS RESULTS

In the study of heavy ion collisions, we have a good reference, which is the nucleon-nucleon (or pp) collisions. A typical quantity is so called nuclear modification factor, of any kind of identified particles. However, in our present case of pp collisions, this kind of measurement are not available. However, similar to the ratio between central collisions and peripheral collisions R_{cp} , special hints can be found in centrality dependent results, *i.e.*, Ridge behavior observation in high multiplicity pp events [5]. To understand those results, let's first check something basic.

In Fig. 2 and Fig. 3, centrality dependent p_t -distribution and rapidity distribution of thermal photons are shown. The centrality is labeled as ν which is the number of Pomerons (a pair of strings is called as a Pomeron). The result is easy to understand: For more central events, more energy is deposited at the reaction region (less energy is brought away by leading particles). Thus more secondary collisions at the reaction region to emit more thermal photons. The same type results on charged hadrons are not shown, but the centrality dependence is similar. We simply parameterize the obtained pseudorapidity density of charged hadrons $dn/d\eta|_{\eta=0}$ as a function of centrality ν :

$$\frac{dn}{d\eta}|_{\eta=0} = 2.8147\nu + 4.3477.$$

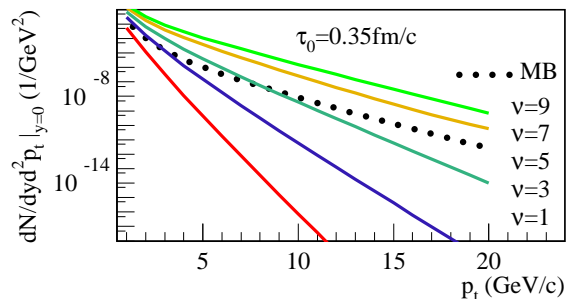


Figure 2: (Color Online) p_t spectra of thermal photons from pp collisions at centrality $\nu = 1, 3, 5, 7, 9$ for solid lines (from down to up). The dotted line gives minimal-bias result.

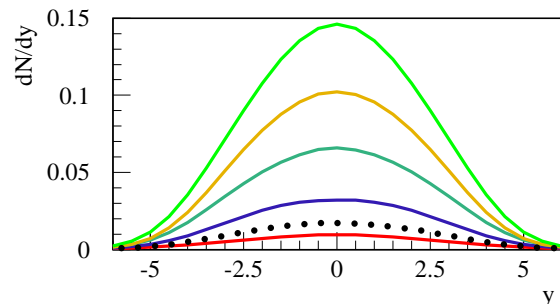


Figure 3: (Color Online) Rapidity spectra of thermal photons from pp collisions at centrality. Same notation as Fig. 2.

What is the consequence after considering the evolution procedure in pp collisions? Let's first review the minimal-bias transverse momentum spectrum of both charged hadrons [7] and direct photons [12]. In Fig. 4 the transverse momentum spectrum of charged hadrons from pp collisions at 7 TeV without evolution procedure (dotted line) and with hydrodynamical evolution procedure (solid line) is shown together with the data points from CMS [6]. We can see that the evolution procedure (the collective flow) has very little effect in charged hadron production. Nevertheless, it is the reason why the Ridge is observed in high multiplicity pp events [7].

Direct photons are much more sensitive to this hydrodynamical evolution procedure, because a completely new source, thermal photons (T), will be added to the conventional prompt photons (P). In Fig. 5 the upper panel, the minimal-bias p_t spectrum of direct photons from pp collisions at 7 TeV is shown in both cases, with hydrodynamical evolution procedure (solid line) and without (dashed-dotted line). The CMS data points [8] are also shown, but not at the sensitive region. The ratio of the two lines are also plotted as solid line in the lower panel. To prove the QGP formation in pp collision, we count only thermal photons emitted from purely QGP phase in the evolution procedure and ignore thermal photon emitted from hadronic gas. The result is plotted in the lower panel as dotted line. We can see that the ther-

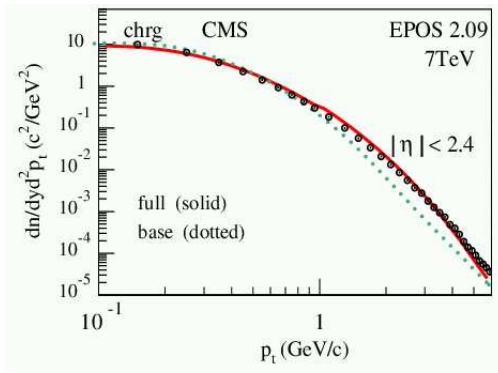


Figure 4: (Color Online) Minimal-bias p_t spectrum of charged hadrons from pp collisions at 7 TeV, without evolution procedure (dotted line) and with hydrodynamical evolution (solid line) are compared with CMS data points [6]. Picture comes from [7].

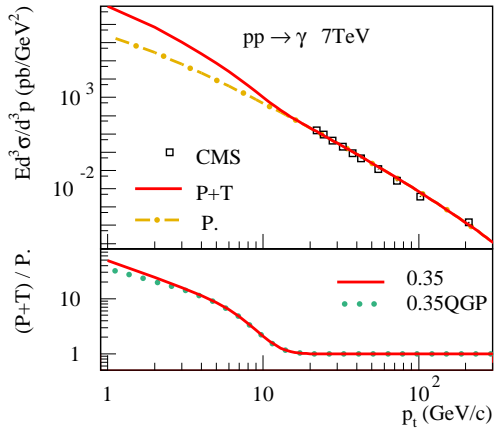


Figure 5: (Color Online) Upper panel: minimal-bias p_t spectrum of direct photons from pp collisions at 7 TeV without evolution procedure (dashed-dotted line) and with evolution procedure (solid line) are compared with CMS data [8]. Lower panel: the ratio of the two lines in upper panel. See text for more details.

mal photons are mostly from the pure QGP phase. This is a direct theoretical proof for QGP formation in pp collisions [9].

IV. CONCLUSION AND DISCUSSION

Centrality becomes important in pp collisions at ultra-high collision energy, because partons at low- x in the proton become more active in particle production. The centrality-dependent p_t spectrum and (pseudo)rapidity spectrum of both thermal photons and charged hadrons show a similar centrality-dependence in heavy ion collisions [10]. Whereas the evolution procedure effects very little in the minimal-bias p_t spectrum and rapidity spectrum of charged hadrons, it has a dramatical influence on those of direct photons, because a completely new source, thermal photons, will be added to prompt photon production at the low p_t region. Additionally, the thermal photons from pure QGP phase is so much pronounced, that it can be proposed as a direct signal of QGP formation in pp collisions.

Although direct photons are heavily polluted by decay photons at low p_t region, special technique has been developed by PHENIX [11] to treat this challenge, which did meet the prediction well [12].

Acknowledgments

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